Rethink of failure of underground construction- lessons learned from Taiwan

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ABSTRACT: Underground construction is widely adopted in urban area but sometimes the construction might cause severely failure. In this paper, successful interpretation of instrument data is addressed and several examples are demonstrated since geotechnical monitoring is thought to be an effective tool to avoid failure. Further, the failure may also be caused by misinterpretation of responsibilities of parties relating underground construction so responsibilities distribution in site investigation, design, construction and geotechnical monitoring are discussed. It is recommended that adequate data of site investigation shall be provided by the client and shall not leave all responsibilities to the contractor. Well- experienced experts shall be invited to evaluate the quantity and quality of data of site investigation before the project goes to tender.

1 INTRODUCTON

Underground construction is widely adopted for the need of underground space due to fast development of urban area in Taiwan but unfortunately disastrous failure sometimes might also be induced. In this paper, successful interpretation of instrument data for underground construction is addressed and several examples are demonstrated based on underground metro in both Taipei and Kaohsiung, Taiwan since geotechnical monitoring is commonly thought to be an effective tool to avoid failure. Further, the failure may be caused by misinterpretation of responsibilities of parties relating underground construction so responsibilities-sharing between the client, consultants and contractors in site investigation, design, construction and geotechnical monitoring are discussed.

2 UNDERGROUND WORKS IN TAIPEI AND KAOHSIUNG

As underground metros in two major cities in Taiwan, Kaohsiung and Taipei were adopted as the background for this paper and a general view of geology and network in both cities are described first.

Taipei is located in northern Taiwan and it is the centre of the political and economic activities in the country. The city is mainly located in Taipei Basin which formed by river deposits from three major rivers, Tahan Creek, Hsintien Creek and Keelung River. Three geological zones surround the Taipei Basin. The Tantu volcano group is to the north, Linkuo Tableland is to the west and the Tertiary sedimentary rocks to the southeast. The total area of the 243 square km Taipei basin has an altitude less than 20 m above the mean sea level. The average elevation of the Taipei Basin is about 5 m above mean sea level. As mentioned above, the basin was filled with river deposits. The base of the Taipei basin mainly consists of sedimentary rock with minor amounts of volcanic rocks of the Tatun volcanic group in the north region of the basin. In cores obtained from a 260m deep exploratory hole near the city centre of Taipei, Tertiary rock was found at 213m below ground level (Wang Lee and Lin, 1987). Hence, the depth of rock bed in the centre of the Taipei Basin is estimated to be around 250 m.

The sedimentary material above the rock may be divided into Hsinchuang, Chingmei and Sungshan Formations. Among them, the Hsinchuang Formation is only found in the western part of the Taipei Basin and includes the alluvial deposits from Tahan Creek. The Chingmei Formation is the alluvial deposit from Hsintein Creek, and consists of 50 to 140 m thickness of gravel. The Sungshan Formation overlies the Chingmei Formation and it was formed of sands and clay deposited by Tahan Creek, Hsintein Creek and Keelung River.

Due to a need of the city, the mass rapid transit system in Taipei (TRTS) was initiated at the end of 80's and the network is still expanding. Most of construction works for TRTS were delivered underground. For underground stations and crossover, the cut- and- cover method using reinforcement concrete diaphragm wall as retaining structures with internal props was adopted and shield- machines were selected for bored tunnels.

Kaohsiung is located in southern Taiwan and it is the 2nd largest city on the island. Figure 1 represents the geology of Kaohsiung City. The city is situated at the mouth of three rivers, Dien-Pao River in the north, Love River in the middle and Chien-Jen River in the south, and as a result the ground conditions in Kaohsiung city are mainly sandy and silty with clay, as depicted in Figure 1.

The network of Kaohsiung mass rapid transit system (KRTS) was planned at late 90's and fully commenced to construct in 2002. KRTS now has two lines and most of them were constructed underground. Similar to TRTS, the cut- and- cover method was adopted for stations and crossover and shield machines were chosen for bored tunnels

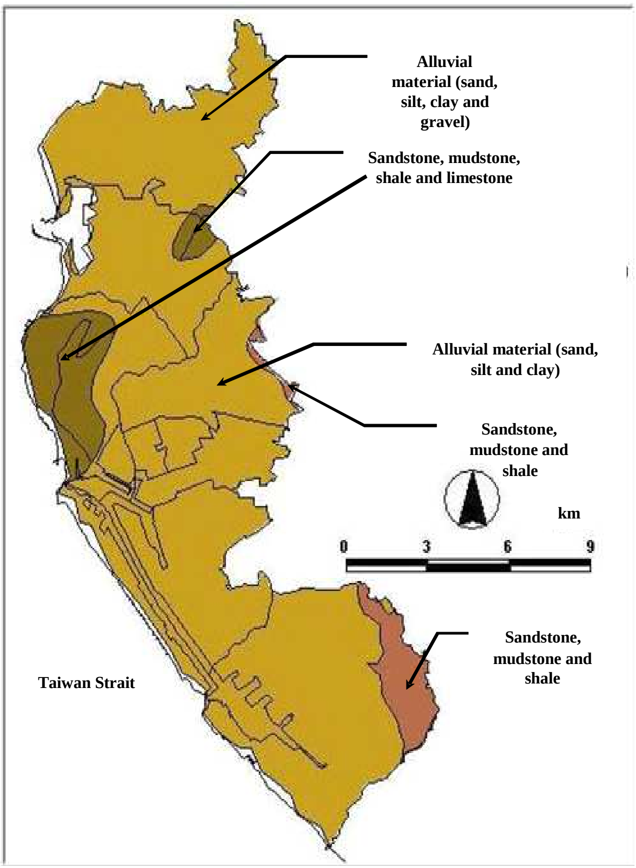

Fig. 1 Geology of Kaohsiung.

3 INTERPRETATION OF INSTRUMENT DATA

Instruments aim to provide useful information to prevent geotechnical failure in advance. Figure 2 presents a typical cross section of geotechnical instruments used for underground works in Taiwan. As presented in Figure 2, instruments generally used on site include inclinometers in wall (SID) and soil (SIS), electrical piezometer (ELP) and standpipe piezometers (PS), observation wells (OW), strain gauge on reinforcement in the wall (RS), load cells on props and bench mark for surface settlement (SM). In order to indicate the performance of adjacent buildings during the construction, tiltmeters and bench mark points on the buildings were installed on the façade of the building to measure the tilting and settlement of the building.

Examples taken from recent underground works in TRTS and KRTS are demonstrated in this paper to express how instrument data are interpreted. In addition, some special measurements taken on site are also reported.

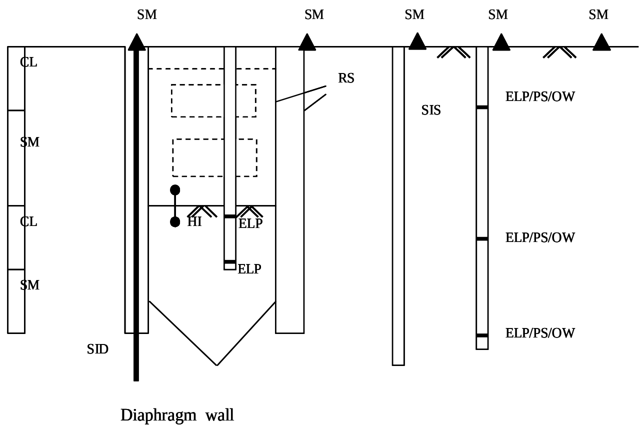

Fig. 2 Typical cross section of geotechnical instruments used for underground works in Taiwan.

Wall deflections were measured at an excavation located in eastern Taipei. The maximum excavation depth of the site is 22.85 m and it was retained by a 43 m deep, 1.2 m thick diaphragm wall. Eight- level internal bracing were adopted to provide additional horizontal supports. It is also noted that depth of bedrock on site was various, from 28 m to 40 m below surface level. It was found that a large wall displacement (up to 115 to 135 mm) was measured and Figure 3 presents a comparatively poor quality of wall constructed on the site. It was constructed using hydraulic- grab type machine and it was reported by the contractor that appearance of rock affects the quality of the wall. Observations here did reflect the quality of wall and this might not be pointed out during the design stage.

Settlements of some buildings near an excavation of TRTS also located in eastern Taipei were observed. It was found that all activities related to excavations were completed but these buildings continued to settle and the reason is unknown. Change of piezometric levels were further explored and it was found that piezometric levels in clay still gradually raise up but not reached the level before commence of the excavation. It was thus recommended that additional effective ground stress due to change of piezometric level should be the reason for additional buildings settlement and these buildings may not remain stable unless piezometric levels fully recovers.

Fig. 3 Quality of diaphragm wall

Figure 4 presents the settlement of the buildings next to excavation of O6 Station in KRTS. Similar to the example taken from Taipei, activities of excavation were completed but the building continued to settle. As indicated in Figure 5, it was observed that pore pressure of ground continued to decrease, though the excavation was completed long time ago and this was thus thought to be the main reason for generation of additional settlements.

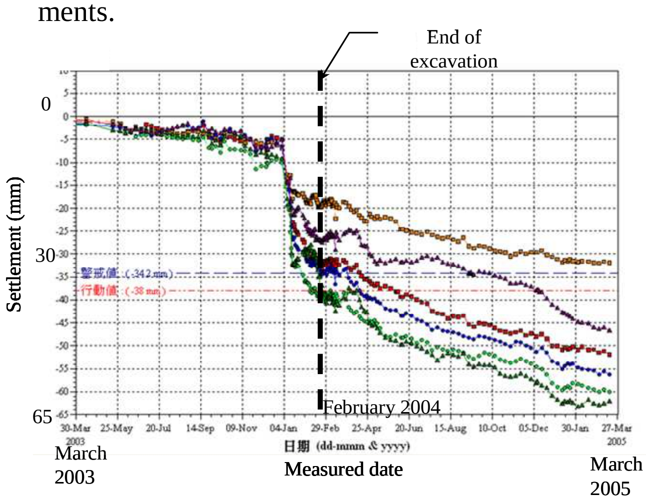

Fig. 4 Settlements of the buildings

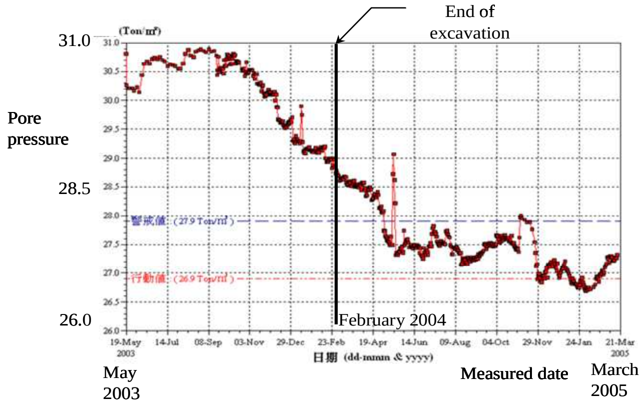

Fig. 5 Change of pore pressure

A large- scale collapse due to construction of cross passage between two running tunnels in Kaohsiung Metro occurred in 2004. An underground pass exactly above metro tunnel was also damaged and has to be rebuilt. It was confirmed that an unforeseen ground characteristic of silty sand in Kaohsiung in relation to soften of soil strength due to disturbance from the excavation is the main reason for the accident.

Some emergency rescue mitigation measures were taken immediately after the accident but reconstruction of the whole project was started approximately 6 months after the accident.

As shown in Figure 6, the central section of the tunnel was constructed using cut- and- cover method and 1.5 m thick, 60 m deep reinforcement diaphragm wall were installed first as retaining structure. The excavation was then conducted by 11 stages. The maximum excavation depth is 30.2 m. After excavation reached final excavation level, precast reinforcement concrete segments were erected on site to build the tunnel as well as cross passage between two running tunnels. Backfill was delivered using the controlled low strength material (CLSM) from final excavation level to bottom of base slab of underground pass to fill space outside tunnels and reconstruction of underground pass was carried out segment by segment.

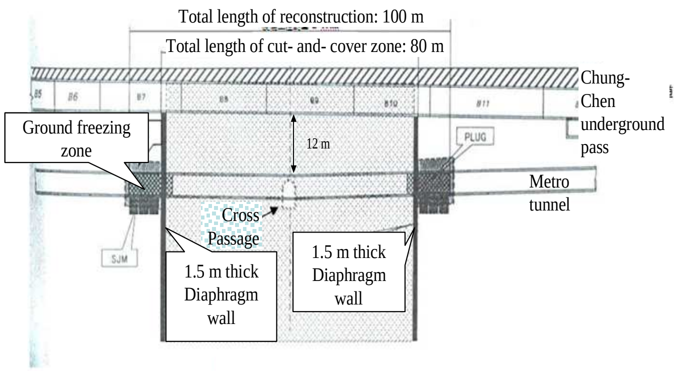

Fig. 6 Cross section of excavation in longitudinal direction

Also depicted in Figure 6, 36 tunnel segments were also affected by accident and have to be replaced but all of them were located outside the cut-and- cover zone, ground freezing method was adopted to freeze the ground in order to stop flow of groundwater and then these segments were replaced.

Thermometers were installed on site in order to confirm the ground freezing was fully completed. Most of thermometers were installed up to 12.0 to 20.8 m below surface level but some of them were installed even deeper, to top of tunnel or into inside the tunnel though a punching hole on tunnel segment. There were 40 thermometers in total and interval between two thermometers varies between 1.8 m to 4.0 m. Such measurement did provide useful indication during stages of ground freezing and replacing tunnel segment.

At last, the other example also in Kaohsiung Metro was raise here to demonstrate the effectiveness of instrument. A 37-year-old building stood 1 to 4 m from a 20.1- m deep excavation and the excavation was retained by 0.8 m thick and 42.0 m deep diaphragm walls. The horizontal props using H- type steel were adopted to stiffen the excavation. Except monitoring of ground performances caused by the deep excavation, structure performance were measured and taken as base of damage assessment. Boscardin and Cording (1989) recommended that the damage to the structure is closely connected with horizontal strain and angular distortion and the device like horizontal tape extensometer, as shown in Figure 7 was used to measure the distance between two nails on façade of the building and expansion or shortening in comparison with previous measurement for the distance between two nails could thus be determined. Horizontal tensile or compressive strain could be interpreted also.

Similarly, the angular distortion was calculated based on measurements of settlements of buildings from various points of the foundation. Hsiung (2009) has approved that results from the damage assessment associated with the method suggested by Boscardin and Cording (1989) were satisfied with observations from the site.

Fig. 7 Measurement using tape extensometer

4 DISCUSSIONS

It is no doubt that success of geotechnical monitoring could prevent failure but failure might also be made because of misinterpretation of responsibility- sharing associated with observations from underground works in Taipei and Kaohsiung. Therefore, responsibility- sharing between the client, designer and contractor in geotechnical investigation, design and monitoring is discussed associated with lessons learned from recent construction of Taipei and Kaohsiung Metro.

First of all, the responsibility of site investigation is discussed, especially in Design- Build and Turnkey (DBT) model construction project. DBT model is a fast- track model for constructing underground work and it has become more and more popular all over the world. In DBT model, the employer (the client) is mainly responsible for land acquisition, access of the site, termination and extension of the contract and payment and leaves most of responsibilities of working performance to the contractor. As the design is also delivered by the contractor itself, the employer is not involved with the design. It is seen commonly that in many DBT model underground projects that the employer conducted very limited site investigations and testing so a clearly picture of ground characteristic could not been detected before commence of construction. However, in Clause 4.11 of the Conditions of Contract for Design- Build and Turnkey prepared by the Federation Intermationale des Ingenieurs- Conseils (FIDIC) "Unforeseeable Sub- Surface Conditions", it states that "If sub- surface conditions are encountered by the Contractor which in his opinion were not foreseeable by an experienced contractor, the Contractor shall give notice to the Employer's Representative so that the Employer's Representative can inspect such conditions….if such conditions were not foreseeable by an experienced contractor, proceed in accordance with Sub- Clause 3.5 to agree or determine:

(a) any extension of time to which the Contract is entitled under Sub- Clause 8.3, and

(b) the additional Cost due to such conditions, which shall be added to the Contract Price.

In fact, ground characteristics might be suddenly changed in a short period due to some external impacts and accident might occur before the contractor could give any notice to the employer or employer's representative. The after- event investigation could also indicate the accident was caused by an unforeseen ground condition and an well- known and experienced contractor are not suppose to be blamed in both cases, though the employer definitely push the responsibilities to the contractor. Moh and Hwang (2007) reviewed some major accidents of underground metro in Asia Pacific and it was found that accidents in DBT model projects might lead 6 to 12 months delay of the project and repair cost could be up to USD 70 million in one project. Many of them were induced by unforeseen ground risk. Knights (2005) presented 15 projects over the period 1994 to 2004, which all faced major ground- related problems with financial losses, in total, of more than 500 million US dollars. Clayton (2001) addressed that evidence from the past shows that construction cost overruns are significantly reduced as expenditure on site investigation is increased. An example taken from Kaohsiung Metro was chosen for further commentary. Figure 8 shows all boreholes of O6 Station of Kaohsiung Metro and it is seen there are 8 holes in the range of 200 m. Only 6 of them were conducted before and during tender stages (in the name of “BO”, “BH” and “OA”) and a full picture of ground conditions for excavations at O6 Station could not be defined by information given here. Due to limit of time in preparation stage, a large- scale site investigation can not be conducted by the contractor so such data have to be well- prepared by the employer. Inadequate data of site investigation may induce the accident and both of the employer and the contractor will suffer from the loss of accident so a “partnership” shall be formed between the employer and the contractor in order to prevent such matter, especially for an underground project constructed in the place never has a similar project before. Considering reasons stated above, adequate data of site investigation shall be provided by the client and shall not leave all responsibilities to the contractor. Well- experienced experts shall be invited to evaluate the quantity and quality of data of site investigation before the project goes to tender.

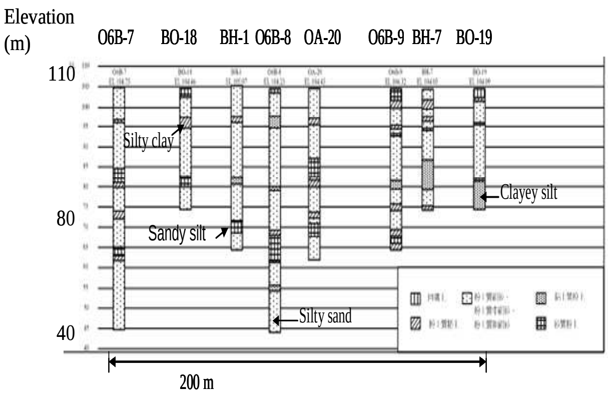

Fig. 8 Borehole information of O6 Station

Second, the responsibility of design is discussed. It is thought reasonably that the responsibility of design shall belong to the designer, no matter recruited by the employer directly or by the contractor. Due to fast development of computer hardware and software, computer- aided design is popularly adopted for geotechnical design of deep excavations and tunnel. Associated with exactly same soil parameters, Figure 9 presents outcome from 2- dimensional and 3- dimensional analytical results of lateral wall deflections with observation of a 19.7 m deep excavation. Difference here might be contributed by different definition of interface used in the software and boundaries and dimensions selected for analyses. Considering observations above, it is concluded that analytical results might be different due to various assumptions of the analytical mesh and model, though the same soil parameters were given. In a large- scale underground construction project, reasonable soil and structure parameters shall be provided by the employer before commence of design as this could possibly increase the reliability and minimize the risk in design, though different assumptions stated above may still induce the difference.

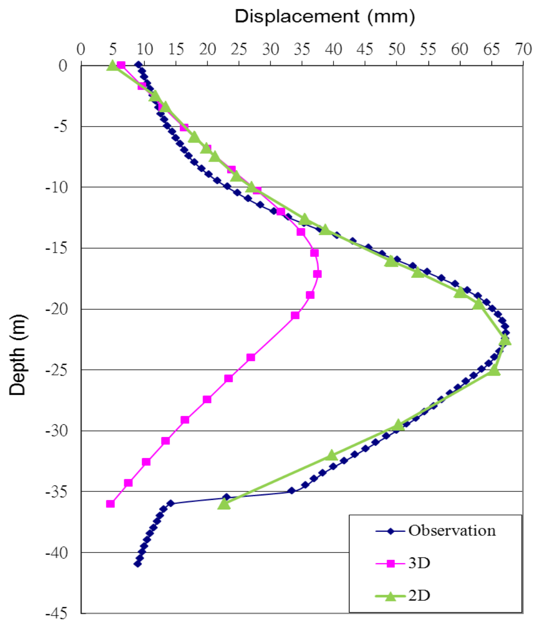

Fig. 9 Analytical wall deflections

Further, as shown in Figure 3, the quality of wall could not be predicted before commence of the design but could possibly be detected after wall installation. The design of the excavation should thus be revised after wall installation because of the quality of wall. Moreover, conducting independent check could increase the reliability of the design and it cost less for design change before commence of construction of an underground project. It is thus recommended that independent checks shall be delivered and revision of design should be concerned from time to time in order to reduce the risk. The employer might not be capable to carry out tasks stated above and it is suggested that special consultants with expertise can be recruited for it.

It is anticipated that most of the responsibility of construction shall belong to the contractor. Recent problems for underground construction in Taiwan include: (1) it is hard to precisely evaluate cost and time of construction before commence of the project as the tender preparation period is very short; (2) low standard of pre-qualification adopted and lowest bid in a very competitive market lead to very limited budget of a project. These are key factors for defects, overrun and delay of construction of underground projects in Taiwan.

At last, the responsibility of monitoring is discussed. In engineering practice in Taiwan, the employer does have a monitoring plan but the contractor is the final decision maker for type, location, depth and quantity of instruments but has to submit the monitoring plan to the designer and the employer to ask for approval. During the construction, a sub- contractor for monitoring is responsible for all site measurements and has to pass all data to the contractor for the first review and then to the designer and the employer for reviews also under certain circumstance. Design change and protection measures of adjacent structures proposed by the contractor are adopted if movements and stress of ground or structure are beyond the warning levels given by the employer. Refer to examples from Taipei and Kaohsiung stated in this paper, the contractor was suppose to provide the reason and solutions but it seems the party was not capable to do so. It is thus suggested that geotechnical experts shall be invited to provide recommendations based on monitoring data from time to time.

As stated above, geotechnical failure might occur suddenly so automatic, real- time monitoring system can possibly pass message to all related parties shortly in order to extend time of response. Hsiung et al. (2011) described an intensive monitoring system using several automatic monitoring instruments for bored tunnels constructed beneath operating taxiway inside the international airport but the reliability of the instrument has to be concerned.

5 CONCLUSIONS

Some conclusions can be drawn based on findings from this paper.

First, successful interpretation of instrument data is addressed and several examples are demonstrated since geotechnical monitoring is thought to be an effective tool to avoid failure. Reliable instrument data can reflect the reality on site.

Second, adequate data of site investigation shall be provided by the client and shall not leave all responsibility to the contractor due to any reason.

Third, in a large- scale underground construction project, reasonable soil and structure parameters shall be provided by the employer before commence of design as this could possibly increase the reliability and minimize the risk. Moreover, conducting independent check could increase the reliability of the design.

At last, it is suggested that geotechnical experts shall be invited to provide recommendations based on monitoring data from time to time. Geotechnical failure might occur suddenly so automatic, real- time monitoring system can possibly pass message to all related parties in order to extend time of response but the reliability of the instrument has to be concerned.

ACKNOLEDGEMENT

The authors want to thank Shanshin Design Corporation for providing data and information of ground freezing in Kaohsiung Metro. The authors also want to thank the efforts of Mr. Fong- Chen Hsieh and Mr. Ching- Hau Chang, Master students of National Kaohsiung University of Applied Sciences for paper preparation.

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